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U.S. NAVAL AIR MISSILE TEST CENTER, PT. MUGU, CALIF.
(TECHNICAL MEMORANDUM REPORT NO. 52)

BARS AS TRAILING-EDGE CONTROL SURFACES - AND APPENDIXES
A AND B

WAGNER, HERBERT A. 15 OCT'51 24PP TABLE, GRAPHS, DRWGS

CONTROL SURFACES - AERODYNAMICS
SPOILERS

GUIDED MISSILES (1)
AERODYNAMICS (4)

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US NAVAL AIR MISSILE TEST CENTER

POINT MUGU, CALIFORNIA

TECHNICAL MEMORANDUM REPORT No. 52

BARS AS TRAILING-EDGE CONTROL SURFACES

15 OCTOBER 1951

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Foreword

The U. S. Naval Air Missile Test Center was established at Point Mugu, California, by the Secretary of the Navy (SecNav ltr Op-24/mad Serial 1873P24 dtd 17 September 1946) effective 1 October 1946. It is an activity of the ELEVENTH Naval District. The Bureau of Aeronautics exercises management and technical control over this activity.

The primary mission of the Naval Air Missile Test Center is the testing and evaluation of guided missiles and their components. NAMTC is assigned cognizance over all facilities at Point Mugu, California, and outlying facilities on San Nicolas Island and the Santa Barbara Channel Islands, collectively referred to as the Sea Test Range.

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summary

Conventional types of control surfaces for missiles are compared with "bars." A "bar" is a small plate placed at right angles to the chord of an airfoil at its trailing edge. Bars, which are also called "trailing-edge spoilers," were used on German subsonic test missiles. Aerodynamic data relative to bars and the influence of bars on the range of a missile are discussed.

It is pointed out that a bar is the only type of control surface that may be expected to combine effectiveness through the sonic range with small activating forces. It is suggested that tests of bars in the transonic and supersonic range are desirable.

introduction

Missiles intended to be used in great numbers should be simple and reliable. Missiles that are designed to hit a fast-moving target or that have a short time of attack must have a control system with short time lags. With conventional control surfaces, it is difficult to meet these conditions. Flaps, furthermore, are unreliable near the speed of sound.

In this report the term "bar" will be used to designate a small plate attached at right angles to the chord of an airfoil at its trailing edge. (See Figure 1.) Such a bar, if deflected from its center position, creates lift, L_b. Bars have been used successfully as control surfaces on German test missiles (Hs 293B, Hs 117) up to Mach 0.84.

Like spoilers, bars need very little energy to move them. A control system with bars has, therefore, small time lags and is consequently simple. The weight of the servos is small. The advantage offered by short time lags is especially large for missiles having automatic stabilization, which requires fast control system response. (Most guidance systems used for fast and accurate control require automatic stabilization even if the missile is already aerodynamically stable.)

At subsonic speed, the parasite drag of a bar is rather small compared to the lift it can create. The main disadvantage of bars is that their parasite drag exists even when no lift is being created. However, the influence of this drag on the range of a missile should in many cases be compensated for by the weight saved in the control system of the missile.

With the exception of airfoil incidence control, a bar seems to be the only type of control surface that may be expected to remain effective through the sonic range. Tests with bars on non-sweptback wings and on sweptback wings near and above the speed of sound should be made to determine their characteristics. The tests made by NACA in the sonic range appear to be inconclusive because the Reynold's numbers were too small.

Unless a particular guidance and control system is specified, it is not possible to make a numerical comparison between the bars and conventional control systems at supersonic speeds. It appears, however, that bars have features which should make them valuable for use in supersonic missiles. For example, it appears that, if bars are used, it would be feasible to locate the longitudinal control at the rear of the missile, thus minimizing the difficult wing aeroelastic problems of supersonic missiles and avoiding tail-wing interference.

conventional types of control surfaces

Flaps

For missile control, conventional flaps have certain disadvantages. Hinge moments and mass are large; therefore, it requires a large amount of energy to move flaps. Especially is this true if they must be moved rapidly, as is usually necessary for missile control. (Hinge moments are dependent both on the angle of attack of the airfoil and on the angle of deflection of the flap; therefore, aerodynamic balance is possible only to a limited extent. Furthermore, at sonic speed, this balance is greatly disturbed.) Near the speed of sound, the effect of flaps often reverses, e.g. if deflected downward, they create a downward force instead of an upward lift.

Airfoil Incidence Control

If a wing or control surface has no flap and control is accomplished by changing the angle of incidence of the whole surface, the effect of control movements does not reverse near the speed of sound. However, mass and forces are extremely large, and complicated and heavy servos are needed to move the surface.

Spoilers

It is possible to design spoilers so that only a small force is required to move them. When deflected, spoilers have large air resistance. Some designs have large resistance even in the neutral position. Furthermore, a considerable time elapses between the deflection of the spoiler and the creation of lift.

At sonic speed their effect becomes uncertain. The decrease of spoiler effectiveness near the sonic speed has received limited investigation in the tests reported in Reference 1. The models were tested only at a near-zero angle of attack of the airfoil; this may be the reason that the problem of control reversal was not experienced.

bars

Structural Design

The structural design of the bars used on German missiles is shown in Figure 2. The bar was a section of a hollow circular cylinder, with the hinge axis located at the center of curvature. Two or three hinges were used for a bar. Long slots were used as rivet holes so that moments of any direction could be transmitted between bar and levers.

The ratio T/H (thickness of bar over its height) was 1/8 to 1/10 for steel; for Duralumin, T/H was chosen about fifty per cent greater. The edges of the bar were well pointed.

Usually, a ratio of H/c (height of bar over wing chord, see Figure 1) of 0.026 was used. However, H/c = 0.04 was also used in a case where an especially large effect was required. The elevators extended over about seventy to one hundred per cent of the span of the horizontal stabilizing surface, and the ailerons extended over about ten per cent of the wing span. In some cases, only one wing was fitted with an aileron.

Performance at Subsonic Speed

Some aerodynamic data for subsonic speeds, derived from tests performed at a Reynold's number of $9 \cdot 10^6$, are given from memory in Appendix A. The properties of bars are comparable to those of spoilers. They have, however, several advantages over spoilers:

Their aerodynamic properties are almost linear. Their aerodynamic time lag is as small as that of flaps. Their effect is quite independent of the angle of attack of the airfoil - in fact, they increase the maximum lift by about the same amount as they increase the lift for zero angle of attack. If deflected in the opposite direction, however, they decrease the maximum lift by only fifty per cent of that amount.

Their effectiveness is almost independent of Mach number up to about Mach 0.88. For slow motion, the energy to move a bar from middle position to extreme deflection, for the German design, was about

$$E = L_{b_{max}} \frac{c}{100,000}$$

where c = wing chord and $L_{b_{max}}$ = lift on control surface created by maximum deflection of the bar. Of this value, about one-half was caused by friction in the bearings (ball bearings were not used), about one-quarter by inaccurate shape of the bars, and one-quarter by air forces acting at the edges of the bar and the levers supporting it. For flap control or for airfoil incidence control, the energy required is at least a hundred times greater.

The ratio $D_b/L_{b_{max}}$ is 1/15 to 1/20 (D_b = parasite drag of the bar), depending on the size of the bar. This is quite a good value. However, the disadvantage of bars is that the parasite drag remains even when no lift is being created.

The trailing edge of the wing in front of the bar was made of solid material, viz., cast magnesium with machined surface. Airfoil buzz or flutter was not experienced in any application. Airfoils were not placed in the wake of a bar.

Influence of the Use of Bars on the Design of a Subsonic Missile

It is relatively easy to estimate numerically the increase of drag when bars, instead of flaps, are used on a missile. The weight saved in the servo system can be established only for a known design of a flap-controlled missile. The increase in performance and reduction in weight of the missile that short time lags make possible can only be determined after a redesign of the control and guidance system of the missile.

The Hs 293 was a German air-to-ground missile with a total weight of 2,300 pounds. The airframe was automatically stabilized in roll, but not in pitch. The shift from flaps to bars made it possible to change from the proportional elevator deflection to a fast-changing full up-down motion, in which the continuous effect was achieved by changing the ratio between the up-time and the down-time. This resulted in faster missile response and in an extremely simple control system. The power required for servos dropped from 350 watts to 50 watts and the weight of control equipment from 150 pounds to 50 pounds. By replacing the battery with an airscrew-driven generator the weight was further decreased, to 30 pounds. This figure includes the weight (about 9 pounds) of the control computer in the missile and that of the servos. It may be expected that similar improvements can be achieved in other missiles. The small power requirements make it possible to avoid the use of hydraulic or pneumatic systems.

The objection may be raised that bars do not permit the short time lags achievable with wing incidence control. Since their maximum lift coefficient is only 0.35, sufficient lift can only be created by using bars at the tail surfaces. However, if some care is taken in the missile design to achieve a small moment of inertia around its pitch axis, the missile time lag need be only 0.15 or 0.2 seconds. Since the lift of most missiles is closely proportional to the elevator deflection, this time lag is well suited to the smoothing of noise. As a rule, the time lag of the highly powered servo systems of wing incidence control is a pure loss - regardless of whether this lag is in the servo systems themselves or applied in front of them for smoothing purposes.

The influence of the drag of bars, compared with that of conventional controls, on the range of a subsonic missile, is investigated in Appendix B. Because of the weight saved in the servo system, missiles with a fairly large angle of climb will gain in range if this saved weight is used to increase the size of the rocket; missiles flying horizontally may lose range.

Performance in the Transonic Range

For the transonic range no test results for bars on non-sweptback wings are available. Hence, such tests appear to be in order. There exist only the results of a test (Reference 2) covering the range up to Mach 1.05 on a 45-degree sweptback wing. In this test the effective Mach number (M_{eff} = 0.75) was considerably smaller than in the wind tunnel tests described in Appendix A. The Reynold's number was below 10^6. Oscillations occurred at speeds near Mach 1.0, and therefore the test results appear to be unreliable. The effectiveness of the bar was considerably smaller than would be expected from the test in the high-subsonic wind tunnel of the Deutsche Versuchsanstalt für Luftfahrt.

Performance at Supersonic Speed

At supersonic speeds, a bar creates a shock wave in front of it (Figure 3). An increased pressure exists in the small region, A, between this shock wave and the bar, and this results in a lift, L_b, on this part of the airfoil. This lift should be independent of the chord, c, of the airfoil, as long as c>A, and of its angle of attack, as long as this angle is small. Wind-tunnel tests should be made to determine L_b and D_b. As no other independent variables are involved, except Mach number (and, to some extent, Reynold's number), such tests should be comparatively inexpensive.

Some information about the values of lift and drag that might be expected can be derived from existing wind tunnel tests and from tests performed in shallow water (see Appendix A). Although this information is in no way conclusive, it indicates that lift-to-drag ratios of 4 may well be expected for a bar on a sweptback airfoil up to a Mach number of 1.7 or 1.8. If the bar is hidden behind the bluntly cut-off trailing edge of an airfoil (see Figure 3, right), the drag of the non-deflected bar can be reduced, especially at high Mach numbers.

In Appendix B, section 5, an investigation is made of the influence that different values of $D_b/L_{b_{max}}$ might have on the range of a supersonic monoplane missile if bars were used as elevators. The feasibility of using bars depends upon the purpose and the design of the missile. As a rule, if the weight of the control and servo system can be reduced by an amount equal to 5 to 10 per cent of the weight of the propulsion system, range will not be lost by using bars. Such weight reductions may well be expected.

Because wings of supersonic missiles usually have a very small aspect ratio, the interference between wing and control surface is particularly high. As a rule, this is combined with some loss (i.e., increase of weight and drag). However, the chord of a control surface in front of a bar can be kept small (Figure 3) and the interference effect thus kept small. With bar control, it appears feasible to locate the elevator on a separate surface at the rear (see Figure 4).

Because of the thinness of supersonic wing sections, it is impracticable to use flaps or airfoil-incidence control for roll stabilization. It should always be possible, however, to mount and operate a bar near a wing tip.

conclusions

The use of bars should be considered whenever a simple control and servo system is desired. Although bars have greater drag than conventional control surfaces, their use makes possible marked reductions in the weight of the control and servo system. Consequently, a net increase in the range of a missile may well result from a changeover to bar control. This will be especially true for missiles that have a considerable angle of climb (e.g., 15 degrees) or a considerable increase in speed during their flight.

In order to answer the question of whether or not bars are feasible for flight at supersonic speeds, the lift and drag coefficients of bars at these speeds should be determined by some simple tests. A lift-drag ratio of 3 or 4 would be large enough to render the use of bars advantageous at these speeds for at least some types of missiles.

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appendix a

appendix a

AERODYNAMIC DATA FOR BARS

Tests with a model having a 10-foot chord (Reynold's number $9 \cdot 10^6$) were performed at a low Mach number ($M = 0.15$) in the large wind tunnel of the DVL (Deutsche Versuchsanstalt für Luftfahrt, Berlin-Adlershof) in co-operation with the Henschel Flugzeugwerke, Schönefeld bei Berlin. These test results are quoted from memory:

The fully deflected bar on a wing with infinite aspect ratio gave a lift coefficient with reference to the wing area in front of the bar, c_L, and with reference to the frontal area of the bar, c_{LAb}:

$H/c = 0.026$	$H/c = 0.04$
$c_L = 0.29$	$c_L = 0.36$
$c_{LAb} = 11$	$c_{LAb} = 9$

For the bar in the middle position, the drag coefficient was about $c_{DAb} = 0.5$ for $H/c = 0.026$, and $c_{DAb} = 0.7$ for $H/c = 0.04$. For the deflected bar, the coefficient for the parasite drag was not accurately determined, but it did not seem to be much higher. Thus the ratio of lift to parasite drag ranges between about 12 and 20.

The lift created by the bar was proportional to the amount of bar deflection and quite independent of the angle of attack of the wing (Figure 5). The maximum lift of the wing was increased by about the same amount as the lift for smaller angles of attack. For large negative angles of attack (Figure 1c), the effect of bar deflection dropped to about 50 per cent of that for positive angles of attack.

Tests in the high-subsonic wind tunnel of the DVL showed that, up to approximately Mach 0.85, the lift was nearly independent of Mach number. The drag coefficient was not determined. The Reynold's number was approximately $2.5 \cdot 10^6$.

No systematic tests at supersonic speeds were made in Germany. Only a very small model, of a tailless missile (Figure 6), was tested in the supersonic wind tunnel of the Aerodynamische Versuchsanstalt, Goettingen. The bar was sufficiently effective to provide control for the missile at the Mach numbers for which the missile was designed ($M \leq 1.4$).

American wind tunnel tests of shock waves in front of cones and of disks are described in Reference 3. The pressure immediately behind the shock wave and the stagnation pressure at the center of the disk are known from theory. Knowledge of these pressures permits a good estimate to be made of the pressure distribution in the space in front of the disk. The force on an airfoil in front of a "bar" of the shape of a half disk, and hence the drag of this bar, can then be calculated. (The pressure behind the bar was assumed to be zero.) These forces are given in Figure 7.

Primitive tests, in which plates were moved through shallow water, have been performed at NAMTC. These tests simulate the two-dimensional flow in front of a plate at supersonic speed. The results were evaluated by the above method and the forces are also given in Figure 7. For low supersonic Mach numbers, the tests gave similar values for lift and drag. At high Mach numbers, however, the wind tunnel tests show a more rapid drop of the lift coefficient. This difference is probably due, in the main, to the difference in gas constants, $\frac{c_p}{c_v}$, for the two tests ($\frac{c_p}{c_v}$ = 1.4 for air, but 2 for the shallow water), and to differences between three- and two-dimensional flow.

Both tests showed that a lift-to-drag ratio of over 2 may be expected for a bar on a non-sweptback wing at Mach numbers below 1.5. Should future wind tunnel tests with actual bars confirm the sharp drop of L/D with Mach number, then the airfoil should be swept back. Sweeping back the airfoil increases the L/D value of a bar not only because of the reduction of the effective Mach number, but also because the drag component in the flight direction decreases by $\frac{1}{\cos \sigma}$, where σ = sweep angle. Thus, L/D values of 5 may possibly be achieved up to a Mach number of 1.6.

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appendix b

INFLUENCE OF BARS ON MISSILE RANGE

1. Method of Comparison:

If the design of a missile is changed from a conventional type of control surface to bars, the range of the missile will be altered. Bars increase the drag of a missile, but their use permits a reduction in the weight of the servo and control system. In the following comparison it is assumed that the entire saving in servo and control system weight is used to increase the size of the power plant. Thus the drag increase introduced by the bars is counteracted by the increase in power plant thrust. The range will be changed by ΔR. Should the saving in weight be just enough, the enlarged motor will be able to deliver the increased thrust for the same length of time, and the range will, consequently, be unchanged, i.e. $\Delta R = 0$.

For the following comparison, it is also assumed that angle of climb, speed, and air resistance of the missile are sufficiently constant to permit the use of average values for the period of its flight. The following symbols are used for the missile with conventional control surfaces:

W = average total weight of the whole missile (includes half the weight of the fuel)

W_P = average weight of the propulsion system (includes half the weight of the fuel)

D = average total drag of the missile, including drag caused by accelerations necessary for guidance

V = average speed of the missile

R = range of the missile

γ = average angle of climb

Δv = increment of speed of the missile during its flight

g = acceleration of gravity

$t = R/V$ = time of flight of the missile

$T = D + W \sin \gamma + \Delta v \cdot W/gt$ = average thrust developed by the propulsion system

$I = Tt$ = total impulse developed by the propulsion system during the flight of the missile

For the design changeover to bars, the following symbols are used:

ΔD = increment of drag

ΔW_s = decrement of weight of control devices and servos

ΔW_p = increment of weight of the propulsion system

ΔI = increment of impulse

ΔT = increment of average thrust

ΔR = increment of range of the missile

It is assumed that, when the design is changed, the speed V and the average total weight of the missile, W, are unchanged and that the weight saved in control devices and servos, W_s, is used to increase the weight of the propulsion system by

$$\Delta W_p = \Delta W_s, \tag{1}$$

thus increasing the impulse, I, by ΔI. It is assumed that

$$\frac{\Delta I}{I} = \frac{\Delta W_p}{W_p} \tag{2}$$

This impulse gain, ΔI, is partly used to overcome the increase in drag

$$\Delta T = \Delta D \tag{3}$$

and partly to increase the range, algebraically, by ΔR.

Before the change, the impulse is

$$I = Tt = T\frac{R}{V}$$

With the change, the impulse changes by

$$\frac{\Delta I}{I} = \frac{\Delta T}{T} + \frac{\Delta R}{R}$$

With Equations (1), (2), and (3), this relation yields

$$\frac{\Delta R}{R} = \frac{\Delta W_s}{W_p} - \frac{\Delta D}{T} = \frac{\Delta W_s}{W_p} - \frac{\Delta D/W}{D/W + \sin\gamma + \Delta v/gt} \tag{4}$$

In case the air density changes considerably during the flight of the missile, the average value of density has to be considered in computing ΔD and D.

If $\Delta R > 0$, range is gained by the change; if $\Delta R < 0$, range is lost.

2. COMPARISON WHEN DIMENSIONS OF BARS ARE KNOWN:

The following symbols are used for the missile with conventional control surfaces:

S = wing area, taken as a reference area for the aerodynamic coefficients

c = wing chord

n = average load factor covering the average acceleration necessary for control

n_{max} = maximum load factor, co-ordinated to $C_{L_{max}}$

$C_{L_{max}}$ = maximum lift coefficient

$(C_D)_n$ = drag coefficient for total drag for the load factor n

q = impact pressure

C_{D_c} = increment of drag coefficient caused by conventional control surfaces of a missile, with reference to wing area.

The dimensions of the bars are given by:

S_b = that part of the total airfoil area, including stabilizing surfaces, that is in front of bars (Figure 1)

H = average height of bars

$A_b = \frac{H}{c} S_b$ = sum of the frontal areas of all bars used on the missile.

NOTE: It is assumed that the trailing edge is only slightly swept.

$C_{D_{A_b}}$ = drag coefficient of a bar with reference to its frontal area.

D_b = drag created by all bars used on the missile.

If

$$D_b = C_{D_{A_b}} \cdot A_b \cdot q$$

$$D = (C_D)_n \cdot S \cdot q$$

$$W = \frac{C_{L_{max}}}{n_{max}} \cdot S \cdot q$$

If $\Delta v = 0$, Equation (4) yields:

$$\frac{\Delta R}{R} = \frac{\Delta W_s}{W_P} \frac{C_{D_{A_b}} \cdot \frac{A_b}{S} - C_{D_c}}{(C_D)_n + \frac{C_{L_{max}}}{n_{max}} \sin \gamma} \tag{5}$$

or

$$\frac{\Delta R}{R} = \frac{\Delta W_s}{W_P} \frac{C_{D_{A_b}} \cdot \frac{H}{c} \cdot \frac{S_b}{S} - C_{D_c}}{(C_D)_n + \frac{C_{L_{max}}}{n_{max}} \sin \gamma} \tag{5a}$$

If the altitude changes considerably over the path of the missile, the average value of air density has to be considered in computing n_{max}.

3. COMPARISON WHEN STABILITY CONDITIONS ARE KNOWN:

The following comparison considers only pitch control of a monowing missile.

Symbols:

n_m = load factor for which equilibrium of moments around the pitch axis exists with undeflected control surface, for a middle value of c.g. position and a middle value of Mach number

d = distance between the center of gravity and the neutral point for same c.g. position

Δn = a change of load factor from n_m

e = the magnitude of the maximum expected change of distance between center of pressure and center of gravity for n_m. The total relative shift of these two centers may reach 2e

n_{max} = maximum load factor needed for guidance

a = distance between the center of gravity and the location of L_c

L_c = the lift on the control surface that must be created in order to establish static equilibrium of moments:

$$aL_c = Wd\,\Delta n + We\,(n_m + \Delta n)$$

L_{co} = maximum value of L_c. For n_m = ½ max, and for d/e positive (as it must be considered), L_{co} occurs for n_{max}:

$$L_{co} = W\frac{e}{a}\,n_{max}\,(1 + \tfrac{1}{2}\,\frac{d}{e}) \qquad (6)$$

f = a factor (f > 1) representing the reserve of elevator effect necessary to create angular accelerations

$L_{C_{max}}$ = maximum lift on control surface, which must be created by elevator deflection

$$L_{C_{max}} = f \cdot L_{co} \qquad (7)$$

D_c = average parasite drag created by conventional control surface

D_b = parasite drag created by bar elevator

With $\Delta D = D_b - D_c$, Equations (6) and (7) yield

$$\frac{\Delta D}{W} = f \cdot \frac{e}{a}\,n_{max}\,(1 + \tfrac{1}{2}\,\frac{d}{e})\,\frac{D_b - D_c}{L_{C_{max}}} \qquad (8)$$

This may be introduced into Equation (4).

4. NUMERICAL EXAMPLE FOR A SUBSONIC MISSILE:

For an aerodynamically stable subsonic missile, the dimensions of the bars are assumed to be known:

$$H/c = 0.03$$

$$S_b/S = 1/3$$

The drag coefficients are assumed to be:

$$C_{D_{A_b}} = 0.65$$

$$C_{D_c} = 0.0015$$

$$(C_D)_n = 0.04$$

The maximum load factor shall be $n_{max} = 4$; the lift coefficient for n_{max} shall be $C_{L_{max}} = 0.8$.

With these assumptions, Equation (5a) yields the values plotted in Figure 8.

5. NUMERICAL EXAMPLE FOR A SUPERSONIC MISSILE:

It is assumed that the missile is stabilized during the boost phase by additional stabilizing surfaces attached to the boosters. For the remainder of its flight, $e/a = 1/40$ may be considered as a sufficiently high value for a missile that is designed to fly without large control accelerations, e.g., $n_{max} = 2$; $e/a = 1/30$ for a missile with $n_{max} = 6$. For an aerodynamically stable missile, $f = 1.2$ should establish sufficient control reserve for angular accelerations, and for a control-stabilized missile, $f = 1.5$.

In Table I, two types of missiles are considered: a missile flying horizontally at high altitudes with a good glide angle ($D/L + \sin\gamma = 0.2$) and a small maximum acceleration; and a surface-to-air missile having, at an average altitude, a maximum acceleration of 6g and a value of $D/L + \sin\gamma$ of 0.6. The assumptions are summarized in the upper part of Table I. For $D_b/L_{b_{max}} = 0.25$, the weight of control and servo system must be reduced by approximately 10 per cent of the weight of the propulsion system, if the range for both types of control surfaces is to be the same.

As another example may be chosen a short range air-to-air missile which is accelerated by its main rocket in such a way that, at the end of its flight, the speed is 500 ft/sec higher than at launching ($\Delta v = 500$). The time of flight is 12 seconds. For medium altitudes, $n_{max} = 15$, $D/W = 1.5$ are assumed and for high altitudes, $n_{max} = 6$, $D/W = 0.6$. Assuming $D_c/L_{c_{max}} = 0.25$, $D_c/L_{c_{max}} = 0.1$, $f = 1.2$, $e/a = \frac{1}{20}$, $d/e = 2$ and $\gamma = 0$:

$$\Delta D/T = 9.7 \text{ per cent for medium altitudes}$$

$$= 5.7 \text{ per cent for high altitudes.}$$

table 1

Comparison for a Supersonic Missile for $\Delta v = 0$, $D_c/L_{c_{max}} = 0.1$

	Aerodynamically stable missile		Control stabilized missile	
n_{max}	2	6	2	6
$d/e =$	2	2	0	0
$f =$	1.2	1.2	1.5	1.5
$e/a =$	1/40	1/30	1/40	1/30
$D/W + \sin\gamma$	0.2	0.6	0.2	0.6
$\Delta D/W$ for				
$D_b/L_{b_{max}} = 0.4$	3.6%	9.6%	2.2%	6%
$= 0.25$	1.8%	4.8%	1.1%	3%
$\Delta D/T$ for				
$D_b/L_{b_{max}} = 0.4$	18%	24%	11.3%	15%
$= 0.25$	9%	12%	5.6%	7.5%

illustrations

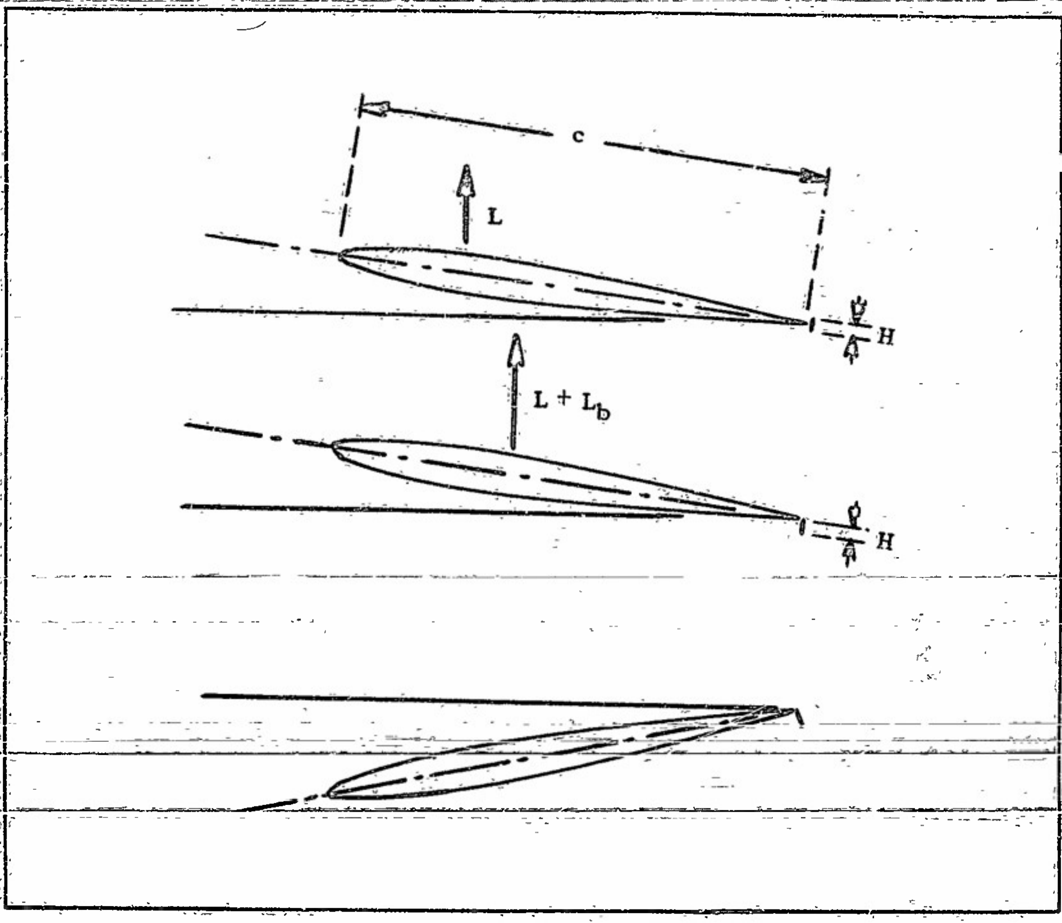


Fig. 1. A "bar" is a small surface attached at the trailing edge and at right angle to the chord. If deflected from its center position it creates a lift L_b.

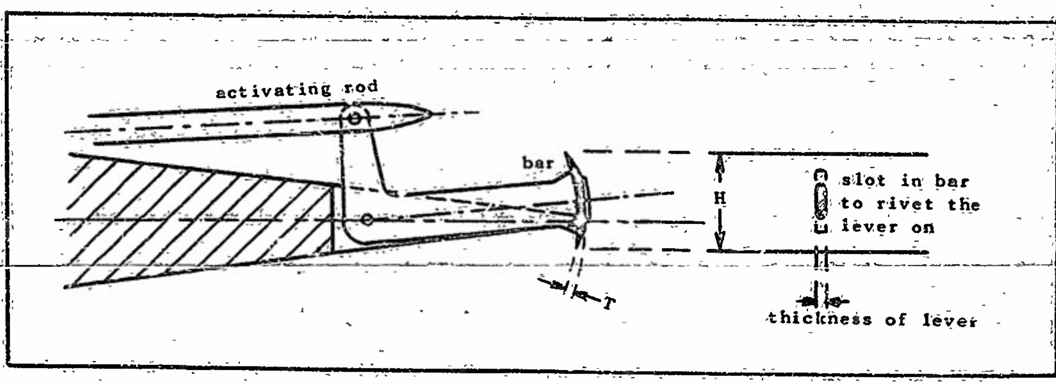


Fig. 2. Structural design of a bar for a German missile.

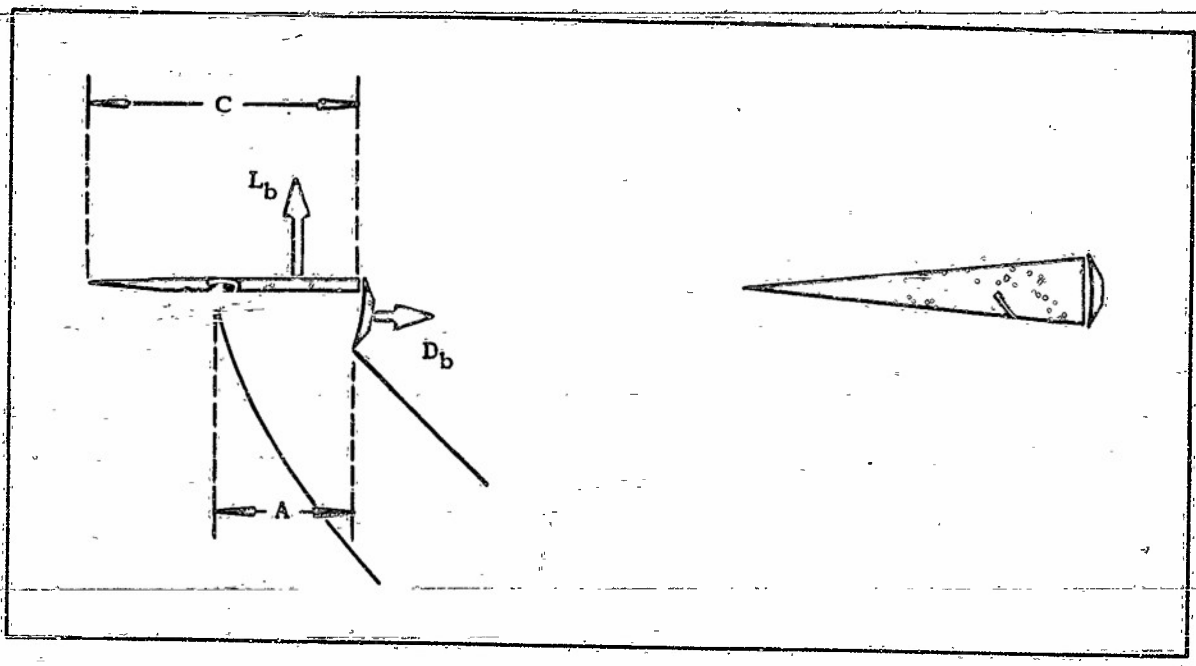


Fig. 3. At supersonic spe[illegible] bar should create a shock wave in front of it and lift L_b. The right hand side design gives less drag of the undeflected bar but higher drag of the deflected bar.

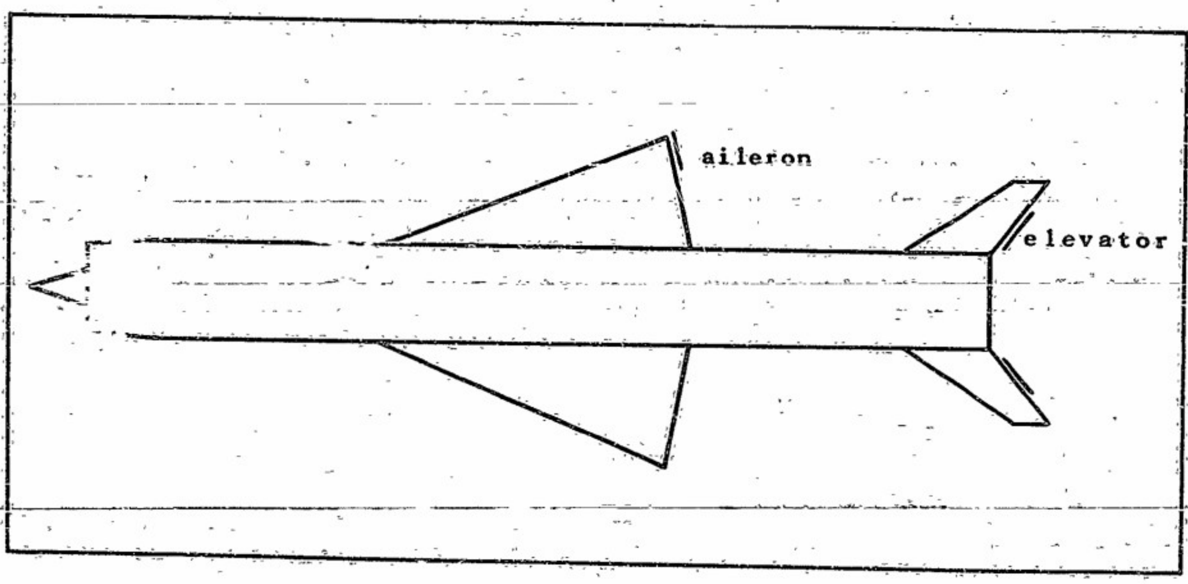


Fig. 4. With bar control it appears feasible to locate the elevator at the tail of a supersonic missile.

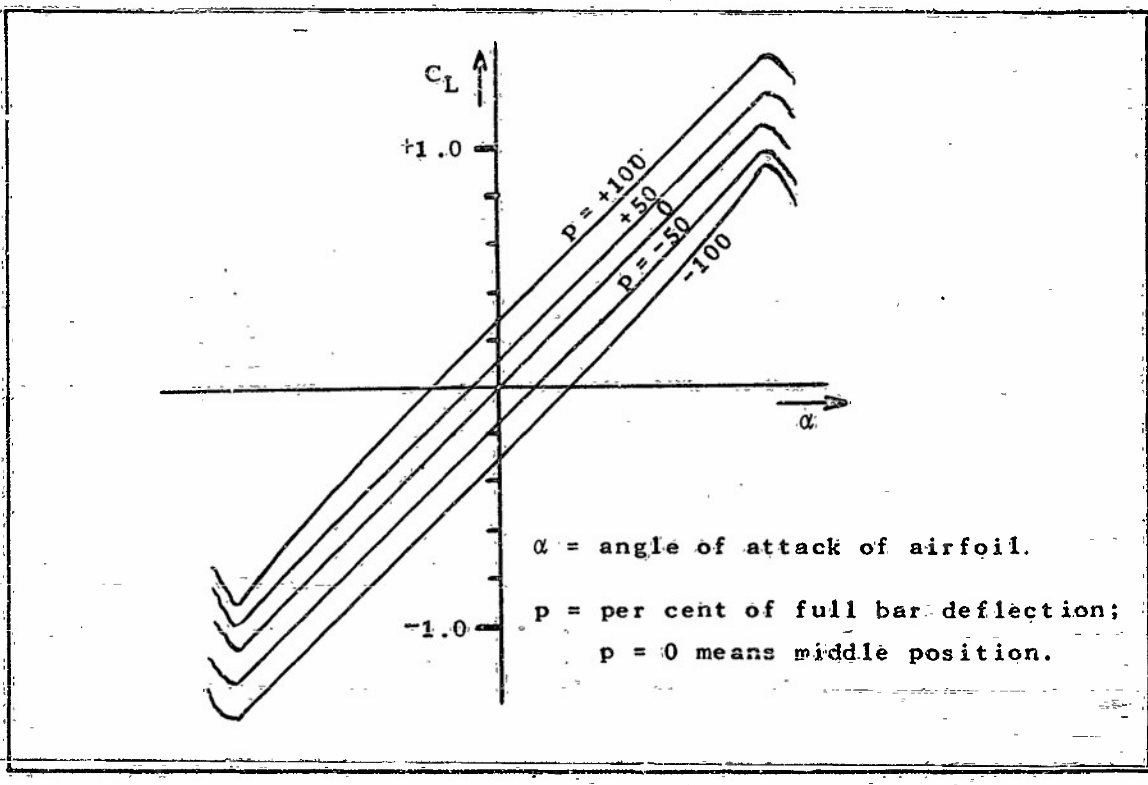


Fig. 5. Lift coefficient, C_L, created by bar deflection at subsonic speed, quoted from the author's memory. H/C = 0.026.

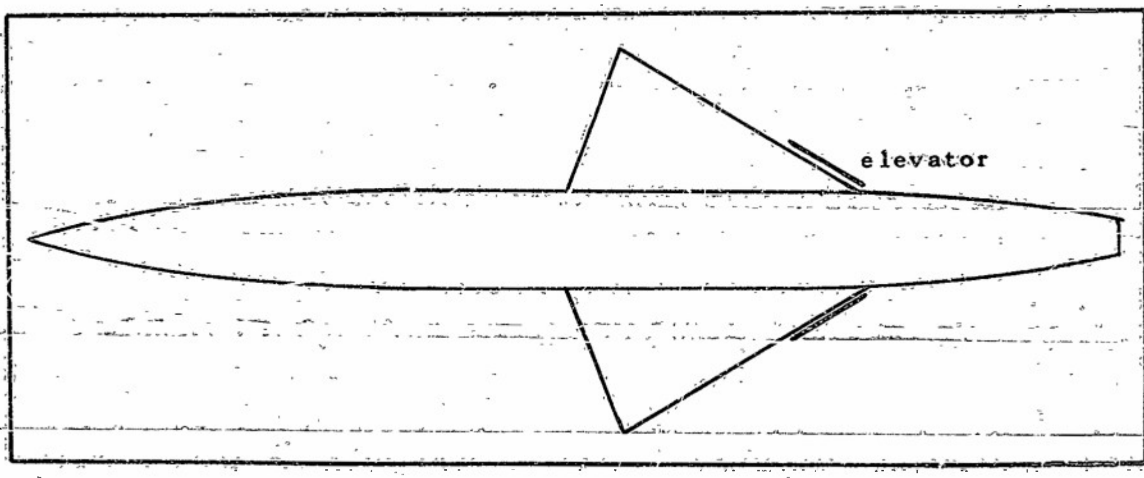
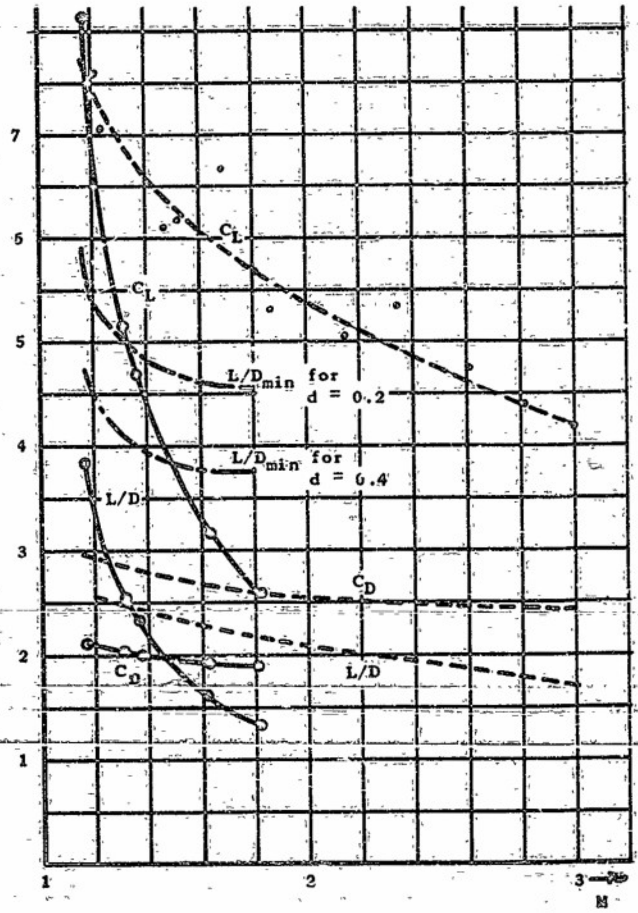


Fig. 6. Wind tunnel model of German missile designed for low supersonic speeds showed sufficient effect of bar elevators.



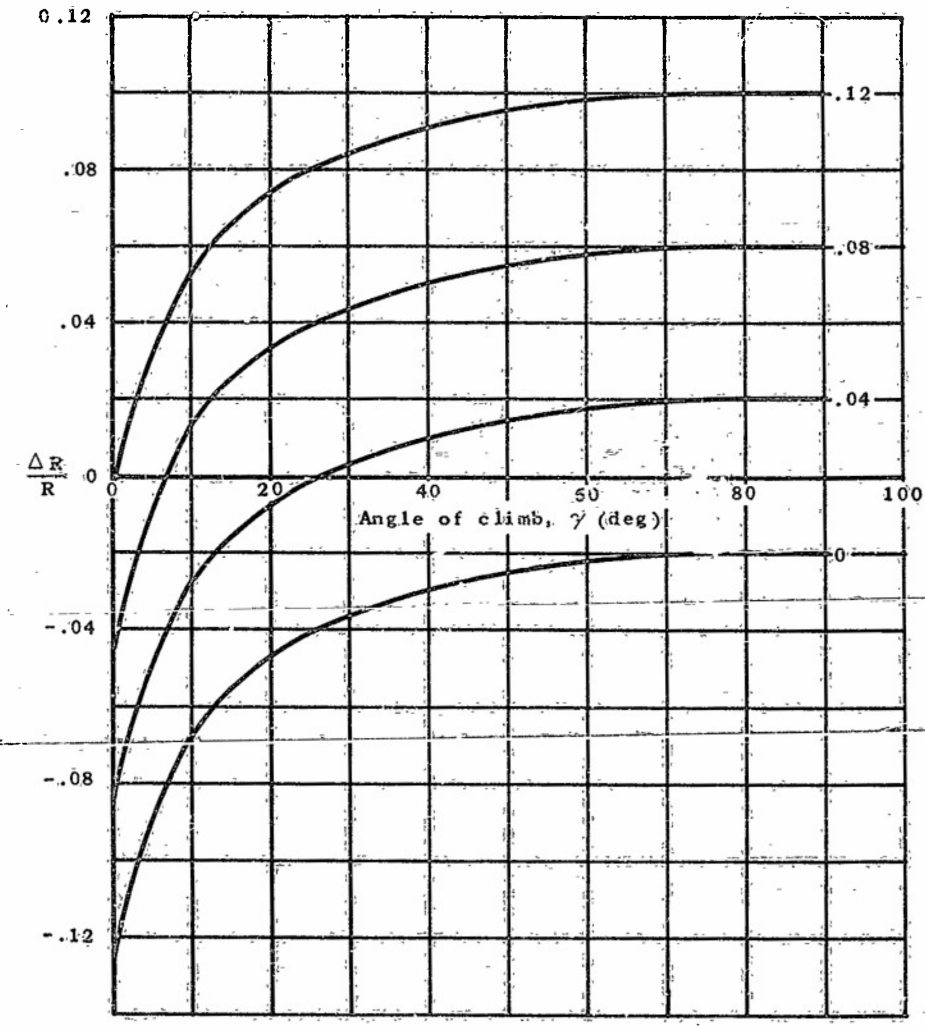
C_D for deflected or undeflected bar behind plate, and C_L and L/D for deflected bar behind plate from evaluation of the wind tunnel tests Ref. 3.

L/D_{min}, where the lift L of the deflected bar is derived from Ref. 3 and the drag D_{min} of the wedge behind which the undeflected bar may be hidden is theoretically computed. The total wedge angle is d:

C_D, C_L and L/D derived from tests in shallow water

In any case, zero pressure is assumed behind the bar. All coefficients are given with reference to the impact pressure and to the frontal area of the bar.

Fig. 7. Lift and drag caused by bars on non-swept wings at supersonic speed.



The perimeter of the curves is

$$\frac{\Delta W_s}{W_p} = \frac{\text{Wt. saved by bar control}}{\text{Av. wt. of propulsive system}}$$

$\Delta R/R > 0$ indicates increase in range resulting from bar control;
$\Delta R/R < 0$ indicates decrease in range resulting from bar control.

Fig. 8. Range comparison for aerodynamically stable subsonic missile.